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High Voltage Packaging Design for Electric Flight Control Surface Actuator Components

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HIGH VOLTAGE PACKAGING DESIGN FOR ELECTRIC FLIGHT CONTROL SURFACE ACTUATOR COMPONENTS

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BACKGROUND

Mission: NASA is developing a plan to build a Re-useable Launch Vehicle (RLV) to replace the space shuttle within the next 10 years. The goals are to make the RLV 10 times cheaper to build and operate and 100 times safer than the existing shuttle. All of the new vehicle's subsystems are being studied to determine safer and more economic designs.

Electric Actuators: Flight control surface actuators and thrust vector control actuators that use primary electrical power rather than a centralized hydraulic power system are candidates for reducing the new vehicle's costs. The Glenn Research Center proposes to develop a system of basic building blocks that can be configured to meet any RLV flight control actuator requirement. The concept uses a system of identical, lightweight (1KW/kg), jam-proof, electric actuator modules with flywheel or capacitor energy storage modules as the basic building blocks. In particular, this approach will:

1. Use identical electric actuator modules for all flight surfaces.
2. Use identical actuator modules to reduce: engineering, development, drafting, documentation, and qualification costs.
3. Use identical actuator modules to reduce spare parts and special training.
4. Combine modules in parallel to increase mechanical capacity and failure tolerance.

Actuator System (**Fig. 1**): A flywheel system supplies direct current electricity through a bi-directional inverter to a three-phase electric motor that drives a variable-displacement pump. The actuator module is completely self-contained with no fluid connections to external systems.

Actuator Module (**Figs. 2** and **3**): The pump is connected to a hydraulic cylinder and piston (jam-proof). The motor operates at constant speed. The pump's bi-directional displacement is controlled by a servo-mechanism. The pump's fluid is supplied from a reservoir and delivered to the linear cylinder to move its piston. To control position, piston position error is used to modulate the pump's displacement control servo.

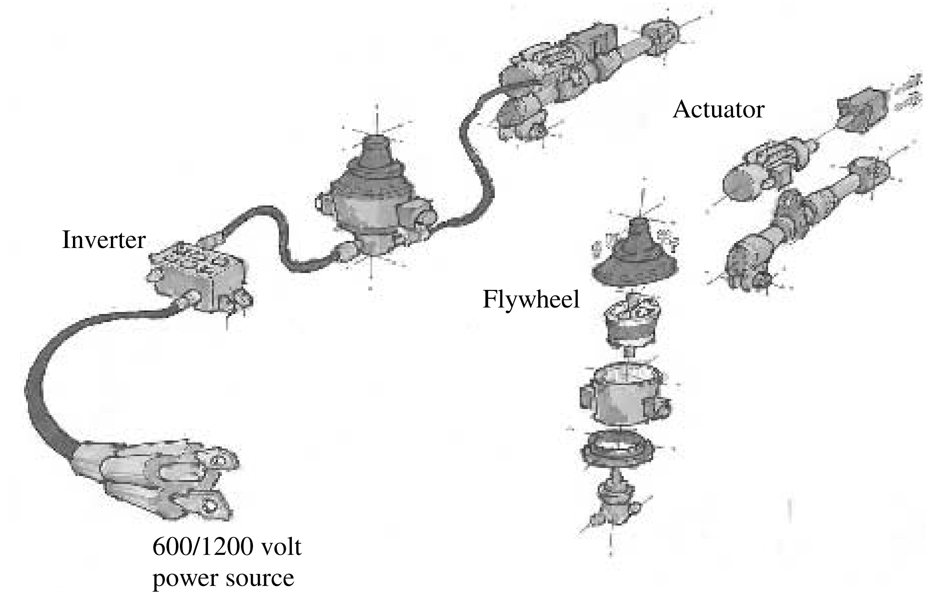

Figure 1. Electro-hydraulic actuator system

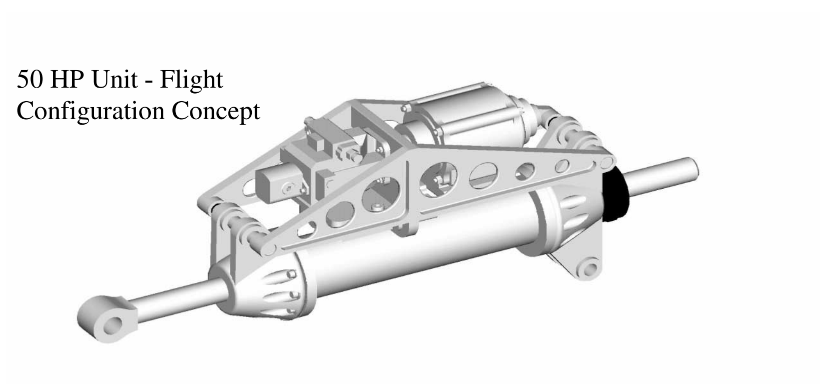

Figure 2. 50 HP electro-hydraulic actuator

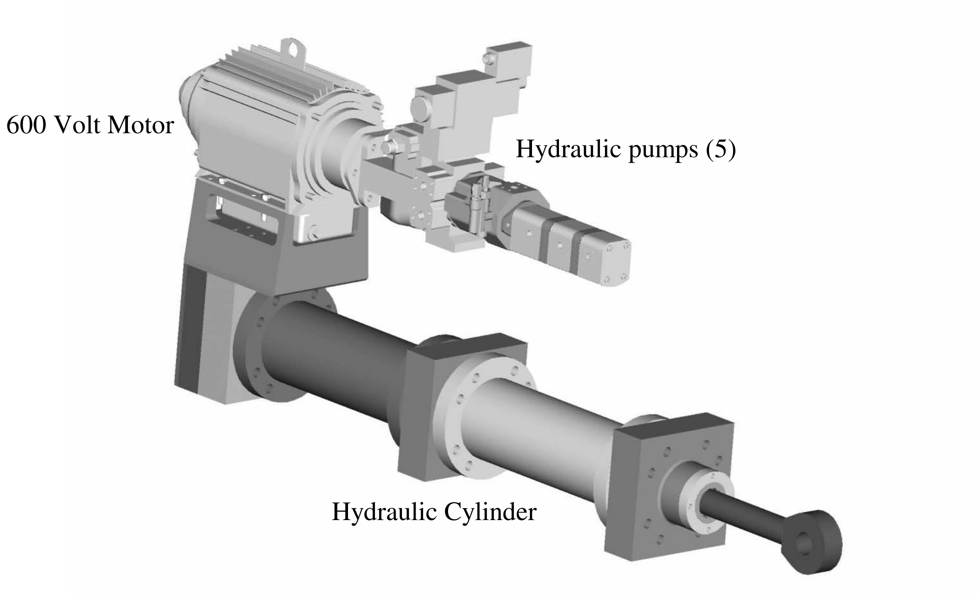

Figure 3. 100 HP development electro-hydraulic actuator

Primary Electric Power System: Electric actuator power estimates for the next generation RLV range from 40 to over 200 horsepower. Such electric actuators both generate and draw large transient power. Space-flight rated power systems that withstand such transients do not exist. A high capacity power system must be developed and tested to capitalize on the cost savings of self-contained, modular electric actuators. The smaller actuator systems will require 300 volts distribution to constrain the power system's weight. RLV concepts that require the 200 horsepower actuators will need 600 volts or more to keep the electrical distribution mass within acceptable limits. These high voltages will cause disruptive discharge during ascent and descent maneuvers unless special packaging concepts are developed.

Power Distribution Unit (PDU) (**Fig. 4**): The Glenn Research Center proposes to design, build, and test a power distribution unit that will control the power delivered to electric-powered flight-control surface actuators. The PDU will house current-limiting power controllers that receive command and control signals from a remote source over a digital communication network. Each power controller will be rated for 20 amperes capacity. Power controllers can be connected in parallel to increase the current-limiting capacity. An external connector module will control the parallel configuration. The PDU will supply the power controllers from either one of two main busses. Transfer switches will control which bus is selected. The PDU itself will be modular using an input module for the two supply busses, their transfer switches, and fuses; a power controller cage to house five power controller modules; and a distribution module to configure the outputs of the power controllers. These three PDU modules will control 100 amperes current at the system distribution voltage. Additional groups of these three modules can be added to further increase the current distribution capacity.

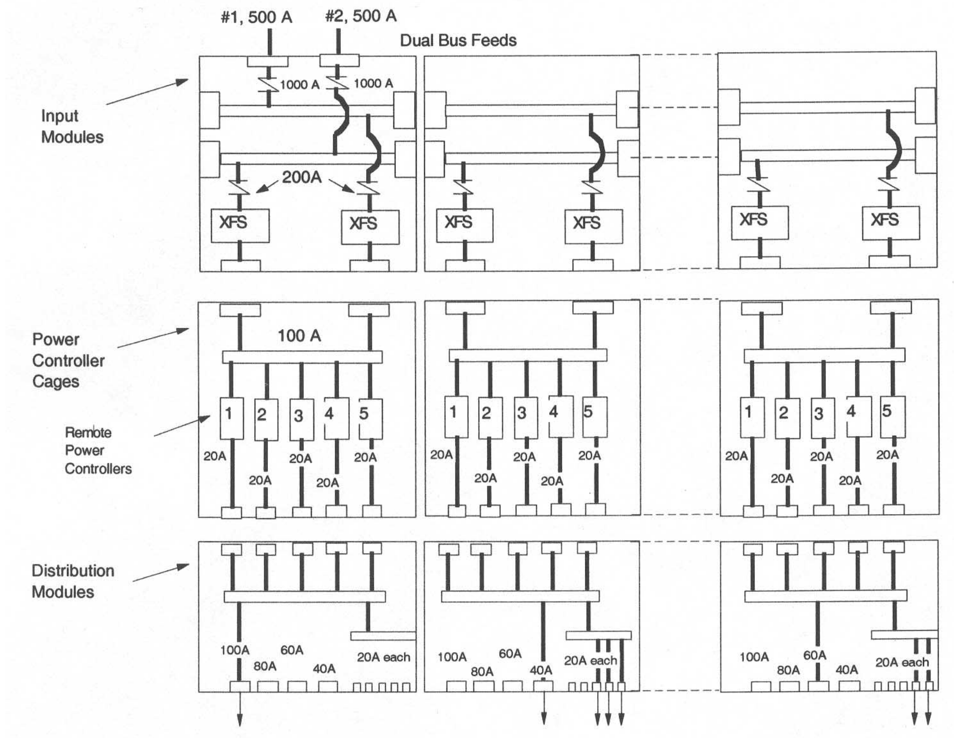

Figure 4. Modular PDU concept (5 assemblies typical)

INTRODUCTION

This final report addresses the high voltage packaging issues and requirements for the Power Distribution Unit (PDU), inverter, motor and associated external wiring, insulation and connectors. Packaging requirements for the PDU (containment, thermal control, component insulation and/or potting, power feed-thrus, connectors and wiring) are essentially the same for the inverter. The motor for the electro-hydraulic actuator is currently cooled and lubricated by the system hydraulic fluid. Current plans are to hermetically seal the motor, gear box and hydraulic pumps in a common package. Requirements for internal motor power wiring and feeds through the hermetically sealed containment vessel will be evaluated as this concept matures.

The Power Distribution Unit (PDU), actuator motor and motor inverter are considered high voltage assemblies. Proper insulation and packaging is vitally important for long life and high reliability. The connectors, wiring and packaging must have suitable insulation that will contain the high voltage to prevent arcing and corona. Arcing and corona phenomena can degrade or seriously damage an electrical system or assembly. **Figure 5** illustrates the Paschen curve of pure gases as a function of pressure times spacing. The pressure corresponding to the minimum breakdown voltage depends on the

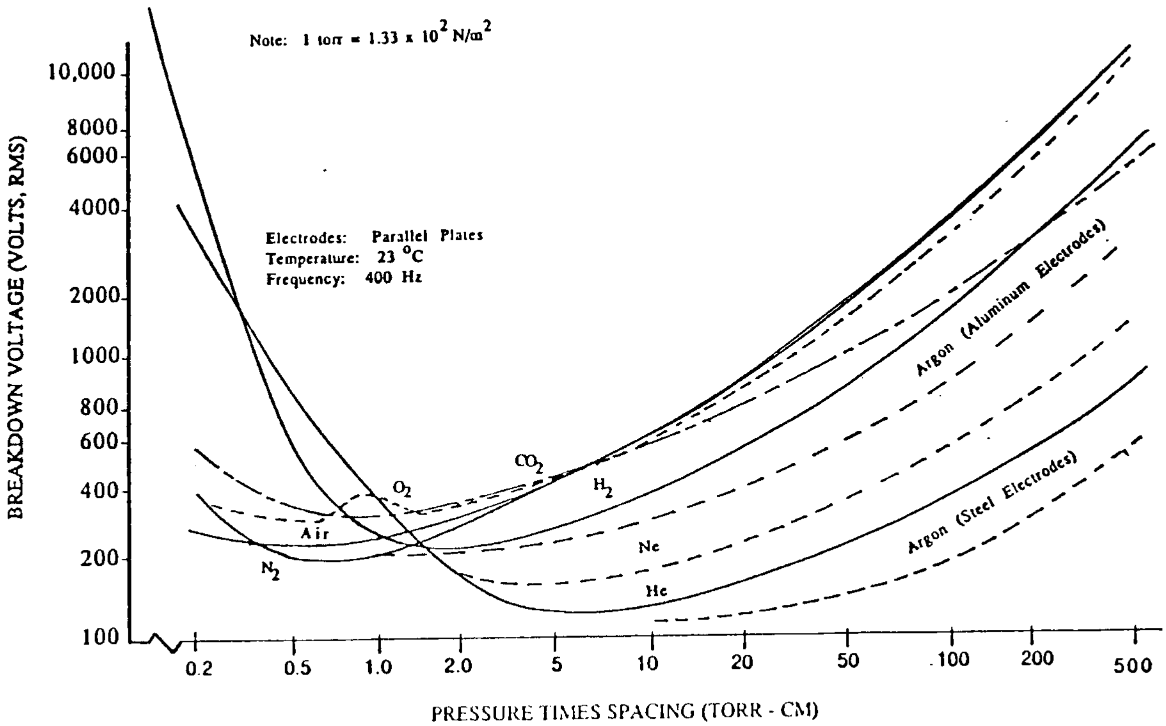

Figure 5. Voltage breakdown of pure gases as a function of pressure times spacing (ref 3)

spacing of the conductors. For air and with a conductor spacing of one centimeter, this minimum occurs at 7.5 X 10^{-3} torr. The breakdown voltage for air at these conditions is 326V. Compare this to a breakdown voltage of 31 KV at standard atmospheric pressure and one centimeter spacing. From this discussion, one can understand the need for proper insulation of high voltage. The operating voltage being considered for these three assemblies and the wiring is 1200 V. This report discusses the packaging of these three assemblies and the design of the external wiring.

External Wiring, Insulation, and Connectors—Partial discharges in electrical wiring generate noise which is conducted to connected equipment. Extensive partial discharges can be coupled into neighboring low-level circuits. The noise signature for partial discharges is typically between 20 KHz and 20 MHz. At high frequencies, the interference generated by partial discharges is worse than at low frequencies. The rate of deterioration of an insulation material by partial discharges is usually proportional to frequency.

The distribution bus, 1200 V, is direct current (DC), however, voltage surges and spikes could be present which can be considered high frequency. At this voltage and considering the possibility that high frequency spikes could be present, special precautions must be taken to prevent partial discharges in the cabling. It is recommended that the high voltage wire be constructed with semi-conducting layers around the stranded center conductor and just within the outer conductor braid. With this type of cable construction, air that is entrapped around the center conductor construction is not electrically stressed thereby minimizing partial discharges.

For high reliability, the dielectric withstanding voltage rating must be at least two times the highest applied voltage. Therefore, the voltage rating for the cabling for the distribution bus should be at least 2400 V. The primary insulation thickness for the high voltage cable will range from 0.1 in. to 0.2 in. with an overall diameter of approximately 0.5 in. **Figure 6** illustrates the design of this cable. The wire size that accommodates 25A of current is 12 AWG, which also includes sufficient de-rating. Space-qualified, high voltage connectors with a voltage rating in the vicinity of 2400 V are not available for 12 AWG wire. It may be necessary to parallel two or more high voltage pins or connectors to provide the capacity for the required current. The power return will not require high voltage insulation but could be included in a multi-pin, high voltage connector to facilitate the connection interfacing. Two manufacturers of high voltage cable and connectors that produce very good and reliable space-qualified products are Reynolds Industries and Connectronics Corp. The estimated costs for developing a suitable connector is approximately $60,000. As of this writing, actual part numbers have not been determined, however, several possibilities are being studied.

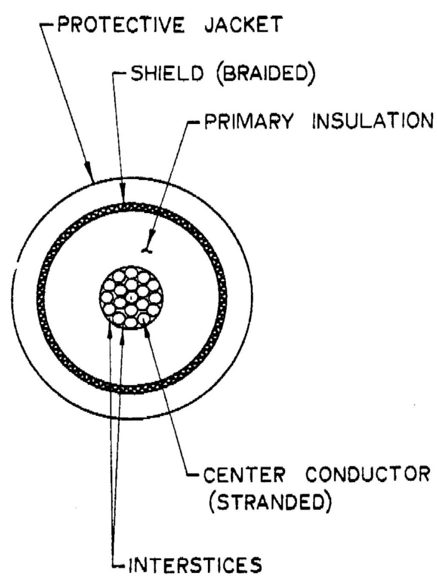

Figure 6. Typical high voltage coaxial cable for minimizing corona

PDU Packaging—The packaging design for the PDU will be based on attaining a ten-year life or greater for the insulation which is accomplished by maintaining a conservative voltage stress on all conductors, high or low voltage. The maximum voltage stress between any set of conductors is determined by their geometry and the type of insulation material. Three types of insulation medium were considered for packaging the

PDU: gas, liquid dielectrics, and solid dielectrics. **Table 1** illustrates a comparison of the advantages and disadvantages these three insulators.

Table 1. Comparison of dielectric mediums

DIELECTRIC MEDIUM	ADVANTAGES	DISADVANTAGES
Gas	• Lightweight • Good dielectric strength • Repairable assembly	• Requires purging and constant maintenance • Must be pressurized • A heater may be required to prevent condensation of gas
Liquid	• Good dielectric strength • Very good thermal conductor • Repairable assembly	• Requires expansion chamber • Must be filtered to remove foreign particles • Maintenance required • Weight increase
Solid	• Good dielectric strength • Fair thermal conductor • Maintenance free	• Some types not repairable • Weight increase

An example of a good gas insulator is sulfur hexafluoride (SF_6). SF_6 is chemically inert and has good thermal stability. However, assemblies using any gas will require purging and routine maintenance.

Mineral and silicone oils are commonly used as liquid dielectrics to insulate high voltage assemblies. Designs that use liquid dielectrics as an insulator require expansion chambers and routine maintenance.

A solid dielectric such as epoxies or silicones is free of maintenance after curing is complete and can easily insulate to 1200 V. Adding a filler to any resin may be desirable as it will increase the voltage insulation and thermal conduction capability of a solid dielectric. It should be noted that most silicones are repairable. When preparing epoxy or silicone resins, it is important to insure that air is not entrapped in the compound or assembly. Partial discharges are possible in voids and will shorten the life of the compound. The best method to ensure that air is not entrapped is by evacuating the assembly and compound in a vacuum chamber. Based upon the advantages and disadvantages of the possible dielectric choices, it is recommended that a solid dielectric be used for insulating the PDU.

A silicone encapsulating material is recommended for packaging the PDU. Silicones are easily repairable and can be removed to replace failed components and connections. Also, a repairable encapsulant will facilitate the testing of the prototype assembly. Currently, studies are being conducted to determine which silicones meet the out-gassing requirements for NASA.

A simplified schematic of the 1200VDC switch is shown in **Figure 7**. All components shown in this figure require high voltage isolation and proper insulation to minimize corona and partial discharges. The average voltage stress between any conductors in the PDU should be 50 V/mil maximum with a peak voltage stress of 150 V/mil between conductors that do not use a printed wiring board (PCB). If using a circuit board, the maximum average stress should be 10V/mil.

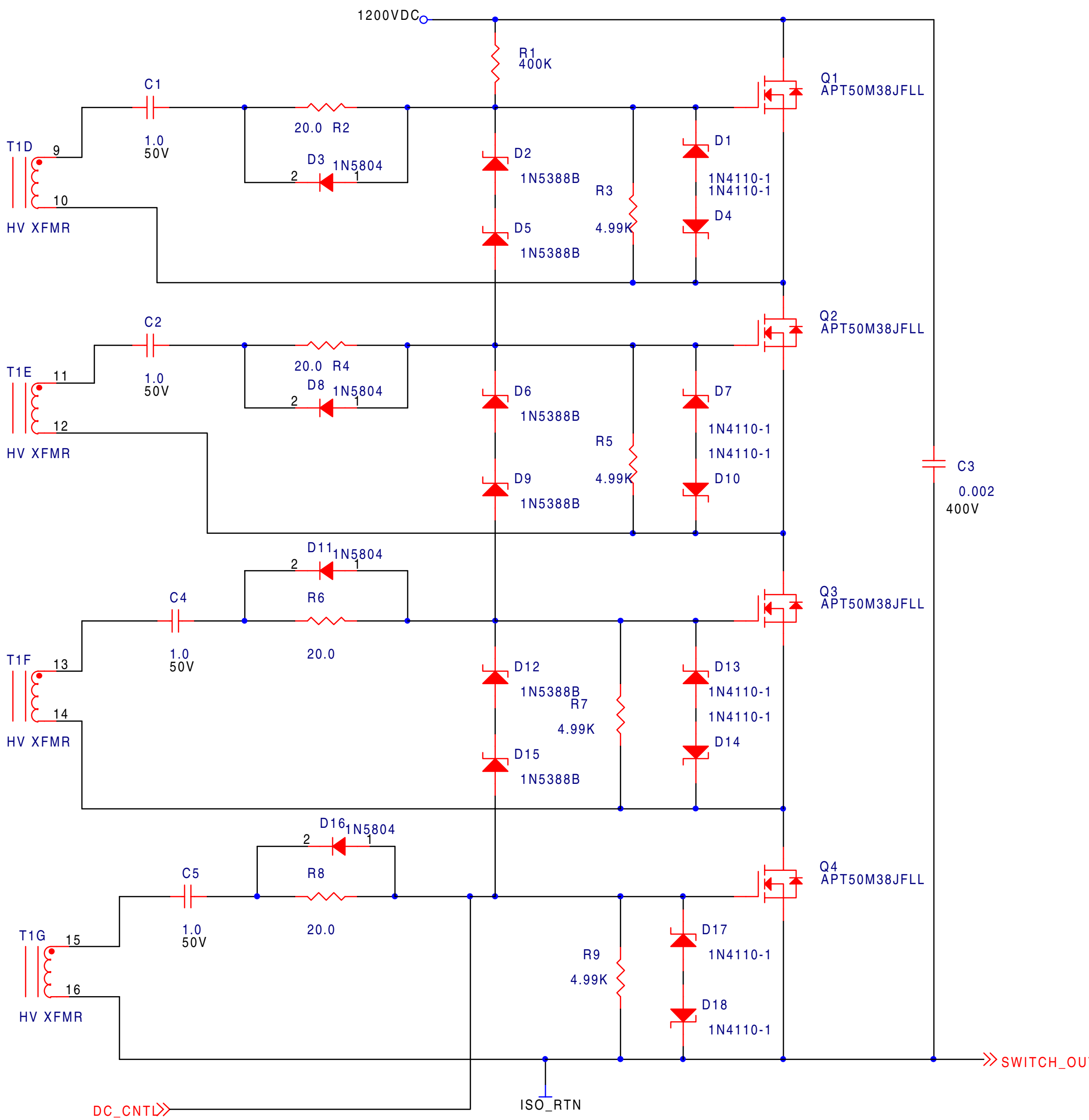

Figure 7. Simplified schematic for 1200VDC switch

Q10, Q11, and Q12 are power Mosfets from Advanced Power Technology (APT) in a SOT-227 package. These devices will be mounted to a heat sink and it is anticipated that all three will dissipate a total of approximately 70 W (at 25A). APT rates the isolation voltage for this device at 3500 Vp, which is sufficient for the 1200 V design.

The average spacing between a conductor at the high voltage potential and a conductor at the return potential should be more than 0.024 in. for the 1200 V Switch. The actual spacing will be determined from the conductor geometry's and may increase from these values.

The recommended packaging design for the PDU consists of two different modules, a power module and a control module. **Figures 8** and **9** illustrate the packaging for the power and control modules, respectively. The PDU will contain one control module and up to 12 power modules. Each power module will be rated for 25 A and 1200VDC. The functions of the control module are to 1) provide the AC and DC drives to the power modules, 2) provide digital control, and 3) furnish the isolated low voltages required by the control module and the power modules.

Actuator Motor Packaging—The motor winding design will be operating at 1200V. Corona or partial discharges could occur in the windings as the vehicle passes through the Paschen minimum in the atmosphere. This is defined as the minimum voltage where breakdown occurs in a gas. The motor under consideration may be saturated using a dielectric oil or pressurized using an insulating gas. Presently, information on the motor design is being studied in order to calculate the maximum voltage stress between all conductors.

Three high voltage insulators are presently being considered for the insulating the motor which are oil and pressurized gas or vacuum. The advantage of the oil will be that it can provide cooling for the windings, however, the disadvantage is that friction and weight will increase.

The second insulation material under consideration is a pressurized gas. The preferred gas is to pressurize the motor package is Sulfur Hexafluoride (SF_6). SF_6 is generally recommended because it is stable, has good thermal conductive properties and is readily available. **Table 2** and **Figure 10** illustrate comparisons of the voltage breakdown for several insulating gases.

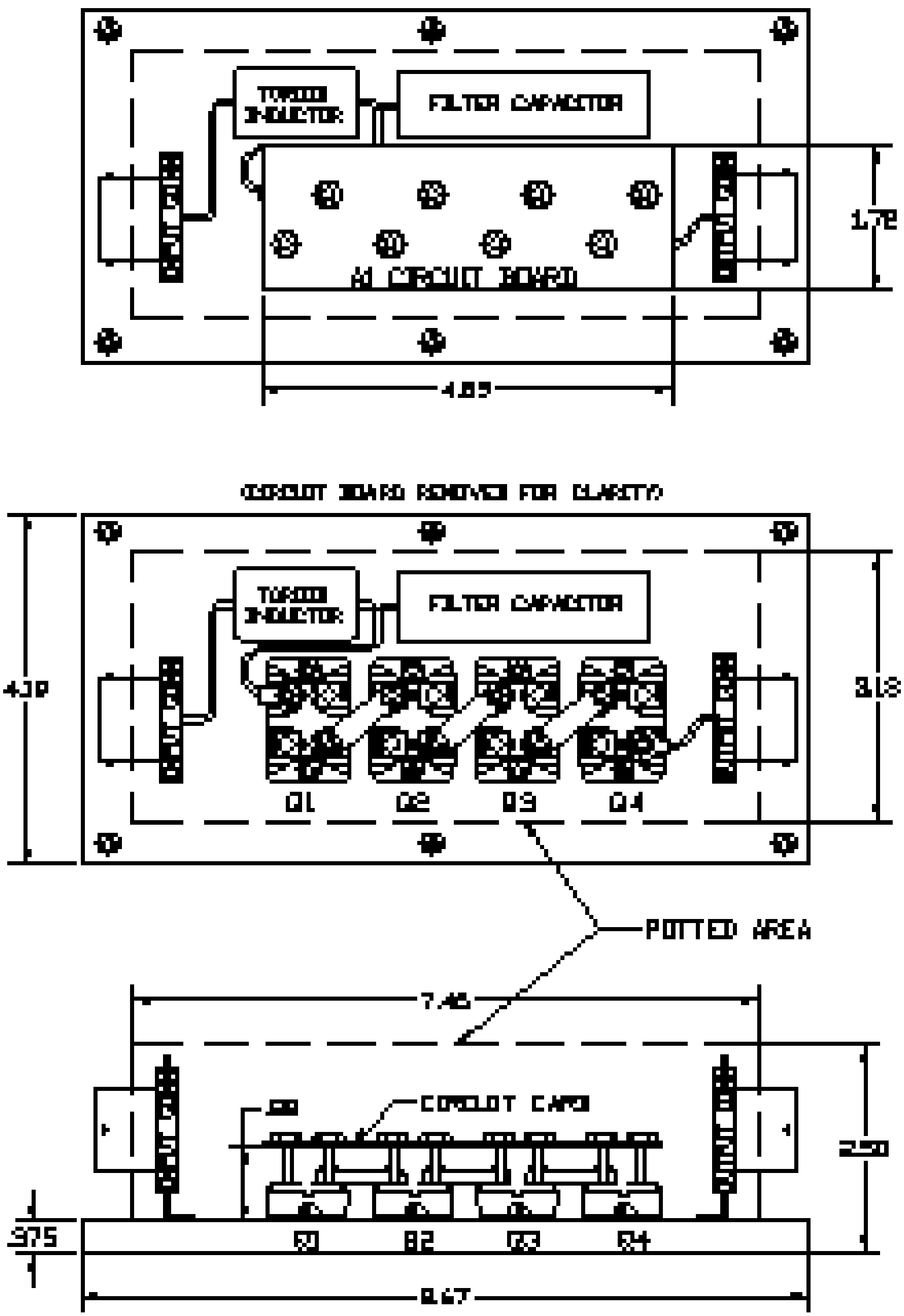

Figure 8. Packaging design for the 1200 VDC, 25 A power module

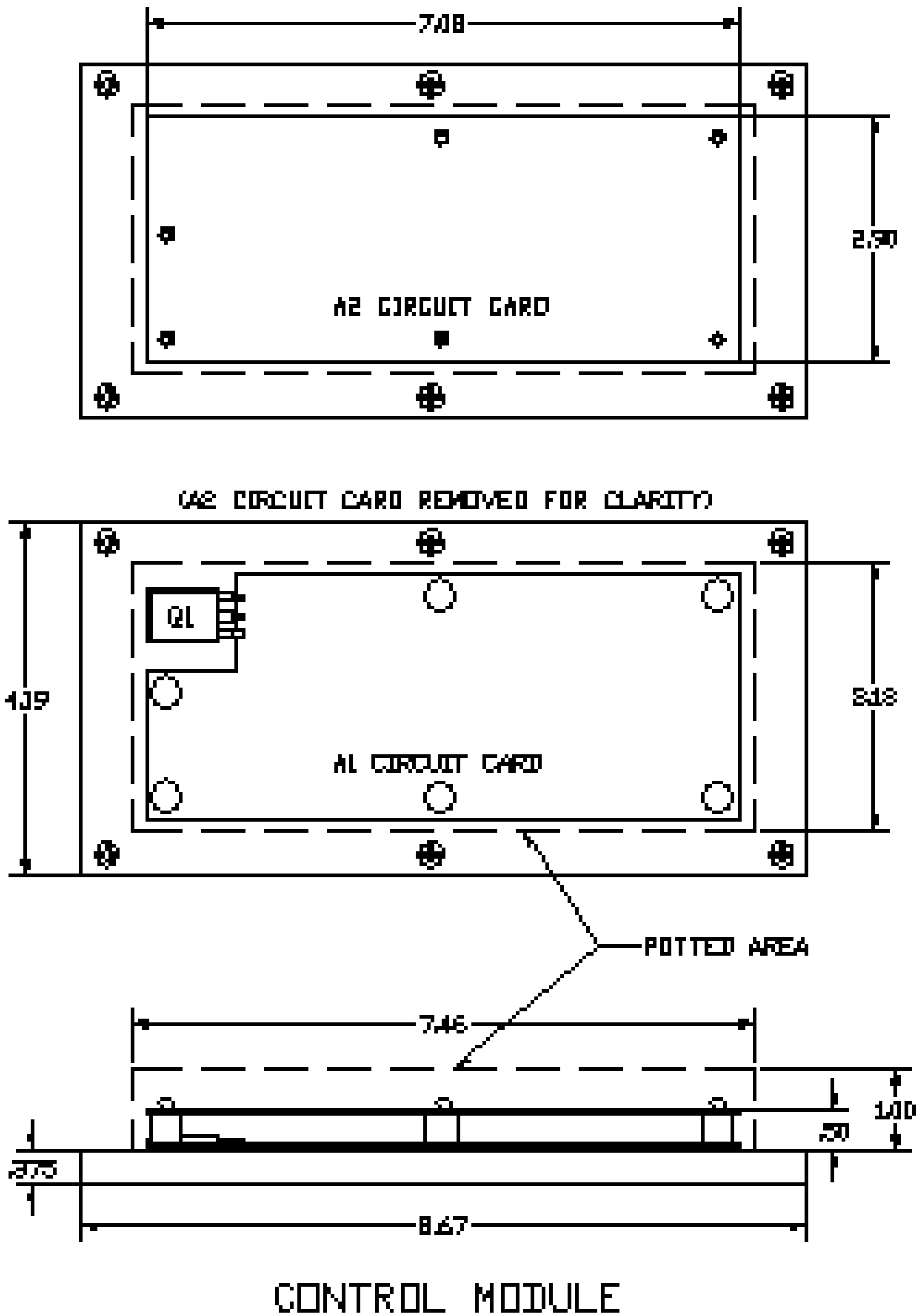

Figure 9. Packaging design for the control module

Table 2. Breakdown voltage between bare electrodes spaced one centimeter (ref. 1)

GAS	MINIMUM AT CRITICAL PRESSURE SPACING	
	V_{rms} (AC)	VDC
Air	223 – 230	315
Ammonia	320	400
Argon	196	280
Carbon Dioxide	305	430
Freon 14	340	480
Freon 114	295	420
Freon 115	305	430
Freon 116	355	500
Freon C 138	320	450
Helium	132	189
Hydrogen	205	292
Nitrogen	187	265
Oxygen	310	440
Sulfur Hexafluoride	365	520

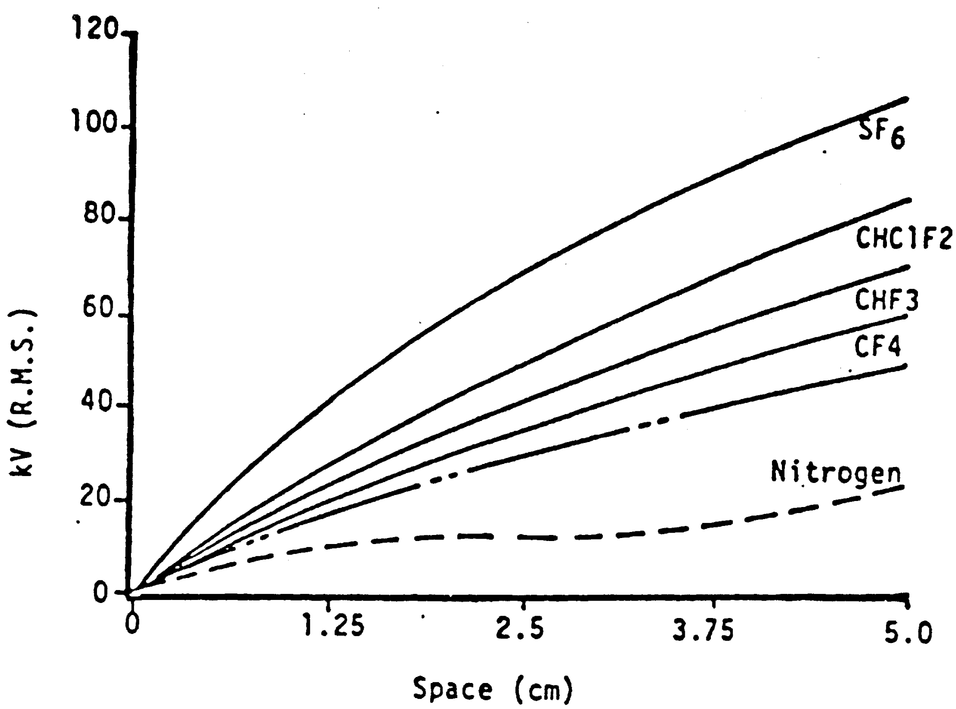

Figure 10. Breakdown voltage curves of gases between a hemispherical-ended rod of 0.1 in. diameter and a sphere of 1.0 in. diameter. Pressure is 1 ATM (ref. 4)

It can be noted that SF_6 has the highest breakdown voltage of the gases listed. The dew point of a gas mixture is important for pressurized gases.

Table 3 shows the dew points for several mixtures of SF_6 and N_2. It may be necessary to install a heater if the gas mixture does not meet the dew point requirement for space applications. Also, a leak-proof seal for the shaft will be required.

Table 3. SF_6/N_2 mixture dew points (°C) (ref. 2)

COMPOSITION OF SF_6/N_2 (VOL. %)	LOADING PRESSURE AT 25°C		
	1 atm	3 atm	5 atm
0/100	-110	-	-
20/80	-92.1	-77.1	-68.9
40/60	-82.4	-66.9	-57.3
60/40	-76.7	-59.6	-50.5
80/20	-72.8	-54.7	-44.1
100/0	-68.7	-50.1	-37.7

The third option is to use conditioned air at a reduced pressure, beyond the minimum Paschen breakdown region. It is not recommended to use other gases (other than conditioned air) at low pressure because they may give off toxic fumes or form corrosive decomposition products. The challenge in using this method of insulation is that is will be difficult to remove the heat from the windings and provide a leak-proof seal for the shaft. However, it is possible to impregnate and encapsulate the windings to insulate and provide a thermal path to a heat sink. Studies are under way to determine the optimum insulating method. It is recommended that corona tests be conducted on the motor to verify the insulation design.

Motor Inverter Packaging—The packaging and insulation design for the inverter will be similar to the PDU. A solid encapsulant with good thermal properties is the preferred method. Refer to the discussion for the PDU Packaging.

CONCLUSIONS

The insulation and packaging of the PDU, Motor and Inverter are being designed for a ten- to twenty-year life to insure high reliability. The wiring, connectors and encapsulating material are being studied and evaluated. Final selection of these components will be made at a later date. The mechanical packaging of the PDU, Motor Inverter and Actuator Motor are being reviewed to ensure that proper insulation and spacing between conductors exist to minimize corona and partial discharges. Corona tests should be conducted on all three assemblies to verify the insulation design.

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13. ABSTRACT ***(Maximum 200 words)***

This report addresses the concept for packaging a 1200V solid-state power controller for use in a space environment.

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